ONR GRANT NO. N00014-91-J-4017

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2. **Title of Project:** The Numerical Simulation of Marine Boundary Layer Clouds

3. **Research Goal:** To obtain a better understanding of the formation, evolution and dissipation of marine boundary layer clouds.

4. **Objectives:** The primary objectives of the research are to numerically simulate stratus, stratocumulus, and cumulus clouds in the marine boundary layer. This includes the formation, evolution, and dissolution of the clouds and the area covered by the cloud fields. If a large enough domain can be covered, then the change from one type of cloud to another would be investigated. Also the change from open cell to closed cell type convection and the formation of cloud streets could be investigated.

   Another objective is to increase our understanding of conditions in the marine boundary layer. What determines the vertical profiles of humidity, temperature, and cloud characteristics in space and time? What causes the changing depth of the boundary layer? What are its interaction with the clouds in and out of the boundary layer?

   A third objective is to compare various numerical models among themselves and with observations. Such comparisons should indicate ways to improve the model and whether practical predictive cloud models for the marine boundary layer can be constructed.

5. **Approach:** Our approach is to use numerical simulations, compared with observations, to help gain an understanding of the basic physics and most important physical processes involved in marine boundary layer clouds. We are use numerical cloud models to do this.

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30 August 1994

Dr. Alan I. Weinstein, Code 1122
Scientific Officer
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Dear Dr. Weinstein:

Enclosed are three copies of our annual technical report under Grant No. N00014-91-J-4017 covering the period 1 September 1993-31 August 1994.

Sincerely yours,

Harold D. Orville

Harold D. Orville, Head
Numerical Models Group

HDO:clh
Enclosure
cc: Administrative Grants Officer (1)
Director, Naval Research Laboratory (1)
Defense Technical Information Center (2)
S. L. Reid
J. R. Miller, Jr.

501 E. ST. JOSEPH STREET, RAPID CITY, SD 57701-3995 USA

6. **Tasks Completed:** The statement last year that the task of applying a traditional two-dimensional cloud model to the marine boundary layer cloud problem was essentially completed was overly optimistic. We have completed a thesis on the topic but further work on the problem has indicated additional studies are needed. One of the major problems encountered was with lateral boundary conditions. We found out at a recent workshop on MBL clouds that the modeling community for such clouds has routinely used periodic boundary conditions. [Trip report attached.] Cloud modelers most often use open boundary conditions, which is what we have used in Kevin McGrath's thesis. For the workshop we also tried periodic boundary conditions which gave us different results. Consequently, we are investigating which kind of boundary conditions give the best results with regard to the types of clouds observed by Betts and Boers.

At the same time we are working on the lateral boundary conditions, we are also running a three-dimensional large eddy simulation to compare with the 2D results. The results of the Workshop indicated many of the statistics of the two types of models were quite similar. The evolution of the stratocumulus clouds were also similar although the details of the clouds were not displayed in many of the 3D models. Chin-Hoh Moeng is the author of the 3D code; she has been very helpful in our studies. She organized the Workshop, patterned somewhat after the WMO cloud modeling workshop of 1992 held in Toronto, Canada.

The World Meteorological Organization has published the final report of the Third International Cloud Modeling Workshop. One of the cases used in the Workshop was the marine boundary layer case applied in this study.

7. **Accomplishments:** A thesis written by Kevin McGrath was completed. The results show the feasibility of applying a traditional 2D cloud model to atmospheric soundings characteristic of marine boundary layer clouds. However, questions remain as to the impact of the lateral boundary conditions on the results, as explained above.

The main conclusions of the thesis are:

1) The "clouds-only" cases produced results that were comparable to the observations. Cloud cover produced was slightly higher than the observations in the broken, cumulus, and "clear" sounding simulations. In these simulations no divergence was included; however, there were indications of subsidence in the observations for these atmospheric regimes.

2) The inclusion of a divergence value of 1×10^{-5} s^{-1} to simulate the effects of subsidence above the cloud layer had a significant effect on the amount of cloud cover present. The greatest effect was found in the broken sounding simulation where a decrease in cloud cover occurred in the simulation. With divergence imposed the cumulus and clear sounding simulations had better agreement with the observations.

3) The drizzle case produced amounts that were reasonable for stratocumulus capped marine boundary layers. The physical effects of drizzle were that it increased turbulent mixing within and below the cloud deck. Evaporation of drizzle below the cloud layer led to areas of instability below the cloud layer. This tended to cause clouds in the simulations to achieve greater cloud depths and liquid water contents.

8. **Statistics:**

Contributed Conference Presentations or Manuscripts:

McGrath, K. S., 1994: Numerical simulations of marine boundary layer clouds. M.S. Thesis, Department of Meteorology, S.D. School of Mines and Technology, Rapid City, SD. 95 pp.

Orville, H. D., F. J. Kopp, and M. D. Vander Vorste, 1994: Comparison of cloud model and LES model results. Presentation at NCAR/GCSS Workshop on Boundary Layer Clouds, 16-18 August 1994, Boulder, CO.

WMO Report on the Third International Cloud Modeling Workshop

Graduate Students Supported

Kevin S. McGrath, second year Master of Science degree graduate student.

Michael D. Vander Vorste, first year Master of Science degree graduate student.

26 August 1994

MEMORANDUM FOR THE RECORD

FROM: H. D. Orville HDO

SUBJECT: Trip Report

Fred Kopp, Mike Vander Vorste, and I traveled to NCAR by car on the 15th of August to attend the Marine Boundary Layer Cloud (MBL) workshop organized by Chin-Hoh Moeng and William Cotton. The workshop lasted until ~~Wednesday~~ Thursday afternoon. The meeting was attended by approximately 38 persons representing 23 groups.

Chin-Hoh had supplied participants with a stratocumulus sounding to run in their models, either one, two, or three-dimensional. The first day and a half was concerned with various reports and presentations regarding research of the various groups. (An Agenda is attached.) We reported on Kevin McGrath's thesis results plus our preliminary results regarding the use of periodic boundary conditions. Our normal cloud model uses open boundary conditions, whereas MBL modelers routinely use periodic boundary conditions. We are obtaining different results depending on the type of boundary conditions used. The conferees could offer us little advice as to why the differences.

The last day concentrated on the results of the various models. Chin-Hoh summarized the 3D model results. Most models took about one hour of real time simulation to reach steady state conditions. There was quite a variation among the 3D models in some of the statistics with the CSU model showing most of the extremes. Cloud cover ranged from 80% to 100%, layer averaged buoyancy flux ranged from 2 to 20 W m^{-2}, liquid water path from 10 to 40 g m^{-2}, liquid water contents of 0.1 to 0.3 g kg^{-1}, total water flux of 100 W m^{-2}, buoyancy flux of 50 W m^{-2}, turbulent kinetic energy (TKE) of 0.4 m^{-2} s^{-2}, and average updrafts and downdrafts of magnitude 0.5 m s^{-1}. There were several other momentum quantities that were recorded.

Steve Krueger reported on the results of the 2D models. The evolution of the clouds, the mean profiles, and the scalar profiles were very similar to the 3D results. The TKE and the mass flux profiles were different. Steve characterized the 3D models as simulating plumes and the 2D models as simulating rolls. It was encouraging to me to see the similarity in the results of the different dimensional models.

Fred and Mike returned to Rapid City after leaving me at the Denver airport to fly to Big Spring, Texas.

HDO:clh
Attachment
cc: P. L. Smith
R. J. Gowen
F. J. Kopp
M. D. Vander Vorste

AGENDA

NCAR/GCSS BOUNDARY LAYER CLOUD WORKSHOP

August 16 - 18, 1994

16 August -Tuesday morning - Boundary Layer Clouds

Chairperson: Chin-Hoh Moeng

8:30	Bob Gall	Welcome
8:40	Bill Cotton	Objectives of the Workshop
9:00	David Randall	Boundary Layer Clouds in a GCM
9:30	Michael Ek	Cloud Cover Scheme for GCM
10:00	** Coffee Break **	

Chairperson: David Randall

10:30	Christian Jakob (Miller, Tiedtke)	Comparison of the Representation of Boundary Layer Clouds in the ECMWF Model Using a Diagnostic and Prognostic Cloud Scheme
11:00	Wayne Schubert	On the Slope of the Trade Inversion
11:30	Roland Stull (Schrieber, Zhang)	Boundary Layer Cumulus over a Heterogeneous Surface during HAPEX-MOBILHY
12:00	** Lunch **	

16 August -Tuesday afternoon - Case Studies with 1D Model

Chairperson: Wayne Schubert

1:00	Bjorn Stevens	The Case: FIRE data
1:30	David Randall	Tests of a New Bulk Boundary Layer Cloud Model
2:00	Shouping Wang	Parameterizing Boundary-Layer Clouds with a Mass Flux Representation
2:30	Aad Van Ulden (Meijgaard)	Simulations of Nocturnal Boundary Layer Clouds with a Single-Column Model
3:00	** Coffee Break **	

Chairperson: Shouping Wang

3:30	Hans Cuijpers (P. Bechtold)	Determination of the Turbulent Length Scales and the Liquid Water Flux in a Cloudy Boundary Layer

16 August -Tuesday afternoon - Case Studies with 1D Model (continued)

4:00	Peter Bechtold	Towards a unified description of Cu and Sc Clouds in Meteorological Models
4:30	** Adjourn **	

17 August - Wednesday morning - Case Studies with CRM or LES

Chairperson: Ian Sykes

8:30	Steve Krueger	2D Lagrangian Simulations of the Stratus to Cumulus Transition in the Subtropical Marine Boundary Layer
9:00	Malcolm MacVean (P. Mason)	2D and 3D Simulation Results with UK MO LES
9:30	Fred Kopp (Orville, Worste)	Comparisons of Cloud Model and LES Model Results
10:00	** Coffee Break **	

Chairperson: Harold Orville

10:30	Ian Sykes (S.F. Paker)	Application of a Monotone-Preserving Scheme in LES Studies
11:00	Steve Lewellen	The Impact of Increasing Grid Size on LESs of Boundary Layer Clouds
11:30	Pier Siebesma (Hans Cuijpers)	KNMI LES
12:00	** Lunch **	

17 August - Wednesday afternoon - Case Studies with 3D LES (continued)

Chairperson: Steve Lewellen

1:00	Bjorn Stevens (Bill Cotton)	CSU LES (Explicit Microphysics Scheme)
1:30	Yefim Kogan (Doug Lilly)	CIMMS LES (Explicit Microphysics Scheme)
2:00	Andreas Chlond	MPI LES
2:30	Chin-Hoh Moeng	NCAR LES
3:00	** Coffee Break **	

17 August - Wednesday afternoon - Case Studies with 3D LES (continued)

Chairperson: Steve Krueger

3:30	Jacques Pasquier	UK MO LES with a Different Radiation Scheme
4:00	Bill Cotton (or Yefim Kogan)	Comparison of Cloud Microphysics Results
5:00	** Reception (Ice Break) **	

18 August - Thursday morning - Intercomparison of Model Results

Chairperson: Roland Stull

8:30	Chin-Hoh Moeng	Comparison of all LES Results
9:30	Steve Krueger	Comparison between 2D CRM and LES
10:30	** Coffee Break **	
11:00	Peter Bechtold	Comparison between 1D Models and LES
12:00	** Lunch **	

18 August - Thursday afternoon - Next Intercomparison Cases

Chairperson: Paul Mason

1:00	Steve Krueger and Bill Cotton	ASTEX Lagrangian cases
1:30	Ken Davis	BOREAS fairweather cumulus
2:00	Don Lenschow and Wayne Schubert	Observational requirements and strategies

**** ***Workshop Adjourn before 3:30 PM*** ****

Chin-Hoh Moeng and Bill Cotton, Workshop Co-Chairs

Martine Bunting, Coordinator
(FL3 Room 3046, X8992)